# APPENDIX 40

MALCOLM PIRNIE

# Technical Memorandum

Date: July 16, 2009

To: Christopher D. Pomeroy, Esq., AquaLaw

From: Clifton F. Bell, P.E., P.G., Malcolm Pirnie, Inc.

Re: Analysis of January-May Inflows to the Chesapeake Bay during the 1996-98 Period

## BACKGROUND

Under USEPA guidance (40 CFR 130.7), total maximum daily loads (TMDLs) must be developed to attain water quality standards under critical conditions. For many TMDLs, critical conditions are defined as a hydrologic condition of a given return frequency, such as the 7Q10 streamflow or a storm of a specific return period. For the Chesapeake Bay nutrient TMDL, USEPA plans to model attainment of dissolved oxygen (DO) standards for a ten-year period representing 1991-2000 hydrology. The intention is to meet the critical conditions requirement by basing the TMDL on the "worst" 3-year attainment period within the larger 10-year period.

Preliminary model results indicate that the controlling 3-year period is 1996-1998. In Bay segments such as CB4, attainment of DO standards in 1996-98 is projected to require more nutrient load reductions than for other 3-year periods within the 1991-2000 hydrologic period (CBPO, 2009). A question has arisen regarding whether the 1996-98 period represents unusual hydrologic conditions, or more precisely, whether it represents a hydrologic condition of a longer return period than is normally selected to represent critical conditions for a TMDL. This technical memorandum presents an investigation of that question.

It is well established that the magnitude and extent of hypoxia in the Chesapeake Bay is largely controlled by the magnitude of freshwater and nutrient inputs during the preceding winter and spring months (Malone and others, 1993; Boesch and others, 2001). Freshwater input during this period affects the extent of hypoxia not only by conveying a large proportion of the annual nonpoint source nutrient loads, but also by affecting the degree of stratification of the Bay water column. Scavia and others (2006) developed a simple empirical model of Bay hypoxia as a function of nutrient inputs from January to May, and this model is now used annually to forecast the size of the "dead zone" that develops in late spring and summer. The amount of freshwater inflow to the Bay during January-May, therefore, is a useful indicator of hydrologic conditions associated with DO standards attainment.

## METHODS

The daily average input of freshwater flow to the Chesapeake Bay was computed as the sum of daily average streamflows at two USGS stream gaging stations:

- Susquehanna River at Conowingo Dam (USGS 1578310); period of record: Oct 1967 to June 2009
- Potomac River near Washington DC (USGS 1646502); period of record: March 1930 to May 2009

The total inflow to the Bay will be higher than the sum of the inflow at these two stations. However, flows from the Susquehanna and Potomac Rivers together represent almost 80 percent of the gaged inflows to the Bay (Sprague and others 2000), and an even higher proportion of gaged inflows that strongly affect hypoxia in the critical mid-Bay segments. The overlapping period of record for these stations was October 1967 to May 2009, a period of about 42 years. The average daily inflow from January through May was calculated for each year in this period. The average daily inflow from January through May was also calculated for each of the forty 3-year periods within the 42-year period.

**RESULTS AND DISCUSSION**

Results (Table 1) demonstrate that the 1996-1998 period had the highest average Jan-May inflow of the entire period of record, representing the 100th percentile of the data. Because this period represents one of forty 3-periods included in the analysis, the resulting estimate of return period is 40 years.

The 1996-1998 period is so usual because it contains two years—1996 and 1998—that represent the 93rd and 98th percentiles, respectively, of Jan-May inflows. Although it is not extremely rare for any given 3-year period to have one such year, it is rare for any 3-year period to have two such years. High inflows in the year 1996 are partly due to extreme meteorological/hydrologic conditions. In January 1996, warm rains fell on a winter snowpack and caused an event known as the "Big Melt". This event has been labeled an "extreme" event by the Chesapeake Bay Program Office and required special consideration during calibration of the Chesapeake Bay simulation models (Shenk, 2008). Inflows during January-May of 1998 were even higher than in 1996.

USEPA guidance does not define "critical conditions" nor address the issue of reasonable return periods for TMDL development. However, a survey of nationwide TMDL documents reveal that the vast majority of TMDLs are developed for hydrologic conditions that represent return periods of 10 or fewer years. The majority of TMDLs developed for critical low flow conditions have used the 10-year return period associated with 7Q10 or 1Q10 streamflow statistics. The reviewed identified TMDLs developed for high flow conditions that used specific design storms with return frequencies of 1, 2, 5, or 10 years. Based on this non-comprehensive review, no specific TMDL examples were discovered that used a return period of 40 years or higher, although some might exist.

Based on this analysis, the critical condition currently being planned for the Chesapeake Bay TMDL appears to be significantly more infrequent than is normally used for TMDL development. Flow percentiles such as those presented in Table 1 can be used to select alternate 3-year periods that represent critical but not extreme conditions. For example, the 1993-1995 and 1994-1996 periods had very high January-May inflows, but were much closer to a 10-year return period than the 1996-1998 period.

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|---|---|---|---|---|
| 1968 | [illegible] | 22% | | |
| 1969 | 42,438 | 0% | | |
| 1970 | 84,427 | 63% | 61,098 | 5% |
| 1971 | 84,120 | 61% | 70,601 | 26% |
| 1972 | 93,471 | 83% | 87,353 | 77% |
| 1973 | 87,377 | 71% | 88,334 | 79% |
| 1974 | 79,204 | 59% | 86,699 | 74% |
| 1975 | 86,470 | 66% | 84,278 | 69% |
| 1976 | 72,630 | 46% | 79,419 | 54% |
| 1977 | 69,439 | 39% | 76,172 | 38% |
| 1978 | 110,325 | 90% | 84,106 | 67% |
| 1979 | 108,111 | 85% | 95,838 | 90% |
| 1980 | 74,977 | 51% | 97,754 | 95% |
| 1981 | 54,093 | 17% | 79,051 | 51% |
| 1982 | 70,444 | 41% | 66,524 | 13% |
| 1983 | 88,004 | 73% | 70,749 | 28% |
| 1984 | 108,544 | 88% | 89,041 | 82% |
| 1985 | 52,674 | 7% | 83,130 | 64% |
| 1986 | 72,839 | 49% | 78,086 | 49% |
| 1987 | 66,681 | 32% | 64,413 | 8% |
| 1988 | 62,667 | 29% | 67,385 | 21% |
| 1989 | 71,255 | 44% | 66,859 | 15% |
| 1990 | 68,896 | 37% | 67,595 | 23% |
| 1991 | 77,275 | 56% | 72,458 | 31% |
| 1992 | 55,991 | 20% | 67,363 | 18% |
| 1993 | 125,978 | 100% | 86,348 | 72% |
| 1994 | 115,417 | 95% | 99,034 | 97% |
| 1995 | 50,775 | 2% | 97,228 | 92% |
| 1996 | 115,181 | 93% | 93,838 | 87% |
| 1997 | 62,227 | 27% | 76,147 | 36% |
| 1998 | 123,730 | 98% | 100,412 | 100% |
| 1999 | 53,581 | 10% | 79,848 | 56% |
| 2000 | 67,687 | 34% | 81,635 | 62% |
| 2001 | 51,596 | 5% | 57,644 | 0% |
| 2002 | 53,935 | 15% | 57,762 | 3% |
| 2003 | 90,567 | 78% | 65,368 | 10% |
| 2004 | 87,155 | 68% | 77,241 | 46% |
| 2005 | 91,598 | 80% | 89,768 | 85% |
| 2006 | 61,593 | 24% | 80,131 | 59% |
| 2007 | 77,155 | 54% | 76,762 | 44% |
| 2008 | 90,357 | 76% | 76,399 | 41% |
| 2009 | 53,906 | 12% | 73,843 | 33% |

* Running average of the listed year and the two previous years

MALCOLM PIRNIE

# Technical Memorandum

Date: September 15, 2009

To: Gary Shenk, USEPA Chesapeake Bay Program Office

From: Clifton F. Bell, Malcolm Pirnie, Inc.

Re: Evaluation of Monthly Span for Critical Hydrologic Period

It is our understanding that the CBPO is proceeding with additional analyses of the critical hydrologic period issue, following up on discussion of the WQGIT teleconference of September 9, 2009. One of the technical issues discussed on that call was that of the monthly span for defining critical hydrologic conditions. This technical memorandum presents an evaluation of this issue with recommendations for consideration by the CBPO as they proceed with their analysis.

## BACKGROUND

Malcolm Pirnie had originally used a January-May span for the hydrologic analysis, based on Bay-related scientific literature that either explicitly used this period in statistical modeling of Bay hypoxia or otherwise emphasized the importance of the winter-spring freshet in not just delivering loads but also strengthening stratification and setting a starting point for D.O. decline (*e.g.*, Hagy and others, 2004; Scavia and others, 2006; Stow and Scavia, 2008; Seliger and Boggs, 1988; Boicourt, 1992; Boynton and Kemp, 2000). Preliminary analysis by Tetra Tech, as presented on the September 9 WQGIT call, demonstrated that the average monthly stream flow of longer monthly spans (e.g., September-June) had higher $R^2$ values when regressed against DO violations rates. Return periods of critical hydrologic conditions can be expected to be sensitive to the monthly span chosen for averaging. Therefore, it is important to determine what monthly span is the most statistically and mechanistically appropriate for defining critical conditions.

To assist with this evaluation, Malcolm Pirnie performed the following: (1) contacted Dr. James Hagy of the USEPA to determine the basis for the January-May span used in the Bay "dead zone" forecasting model; (2) investigated why inclusion of stream flow from the previous fall might give increased $R^2$ values; and (3) evaluated alternative (non-parametric) means for quantifying the correlation between Bay inflows and DO violation rates. Based on this analysis, we recommend that monthly span start in either December or January and end in either May or June. To address uncertainty with the appropriate monthly span, return periods could be expressed as ranges associated with the four possible monthly spans.

## ORIGIN OF JANUARY-MAY PERIOD

The January-May period is used in a well-known statistical model to predict hypoxia as a function of winter-spring nutrients loads to the Bay (*e.g.*, Hagy and others, 2004; Scavia and others, 2006; Stow and Scavia, 2008). The model had its origin in Ph.D. dissertation work by James Hagy. Malcolm Pirnie communicated with Dr. Hagy on September 10, 2009, and inquired about the basis for the January-May period. Dr. Hagy's response can be paraphrased as follows:

- There is nothing binding about the January-May period specifically; it happened to provide the best prediction of hypoxia for the dataset with which he was working.
- However, mechanistically speaking, it is the winter-spring freshet that is of most interest in determining the potential for summer hypoxia.
- Streamflows as far back the previous September are not expected to have a significant mechanistic-hydrologic effect on summer hypoxia. Higher correlations with such as longer period are probably due to chance.
- The timing of the freshet varies from year to year. It most often occurs in the late winter or spring (Mar-May), in some years, streamflows as early as December can affect the salinity regime and the potential for hypoxia.
- The Jan-May period tends to capture the months that are most often important, although not all these months might be important in any given year.

## EFFECT OF HIGH LEVERAGE DATA ON $R^2$ VALUES

The lack of a strong mechanistic basis for the effect of early fall streamflows on summer hypoxia leads to the question of why the inclusions of these months might increase $R^2$ values of the streamflow-hypoxia regression. The addition of December to the monthly span might actually improve the mechanistic basis of the relation, because in some years December flows might be an important component of the winter-spring freshet, as discussed above. However, $R^2$ value can be very sensitive to individual data points of high leverage, particularly in relatively small datasets such those with which we are dealing. This seems to be the case with the inflow-DO violation rate regression.

Figure 1 is a scatter plot of the 3-year average Bay inflow (Potomac + Susquehanna) v. 3-year DO violation rate developed using 1985-2006 data. Bay inflow averages were computed both as Jan-May and Sep-June averages. The slopes of the two relations are almost identical, and both are highly significant regressions. The September-June regression has a slightly higher $R^2$ value. However, when the single data point associate with the highest DO violation rate (associated with 2003-2005) is removed, the two $R^2$ values are identical (Figure 2). Given the sensitivity of $R^2$ values to individual data of high leverage, we believe that it would be useful to examine the correlations between average streamflow and DO violation would best be examined using non-parametric statistics.

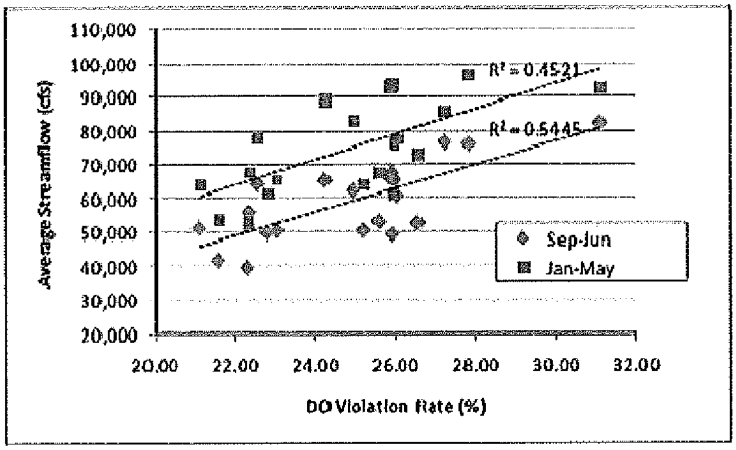


**Figure 1:** Scatterplots of 3-year average Bay inflows v. 3-year DO violations rates, 1986-2006.

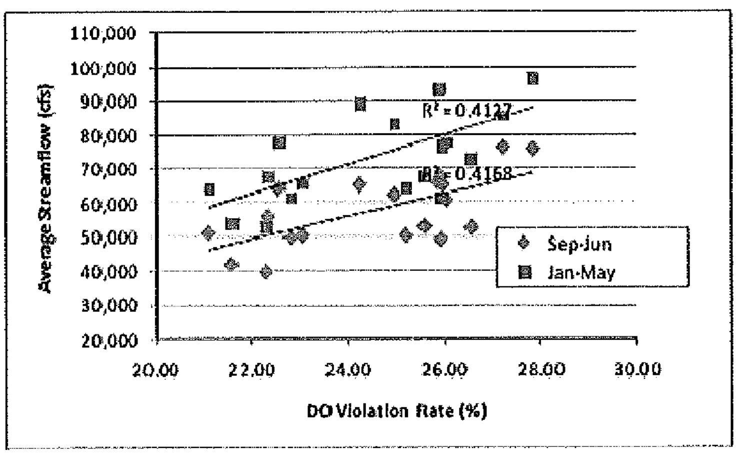


**Figure 2:** Scatterplots of 3-year average Bay inflows v. 3-year DO violations rates, 1986-2006, with 2005-2006 datum removed.

## NON-PARAMETRIC CORRELATIONS BETWEEN DO VIOLATION RATES AND AVERAGE STREAMFLOW

Correlations between DO violation rates and average Bay inflows were computed using two non-parametric statistics: Spearman's rank correlation coefficient, and Kendall's tau. Different monthly spans were used to compute the average Bay inflow, the longest period being January-June and the shortest period being January-May. Results (Table 1) demonstrate that all the correlations are highly significant and in a similar range (0.6-0.7 for Spearman's rank correlation coefficient and 0.4-0.5 for Kendall's tau). The addition of September-November to the inflow did not increase the correlations, and in fact decreased them slightly. The addition of December and January to the January-May period increased the correlations slightly.

**TABLE 1**
**Non-Parametric Correlation Coefficients for 3-Year Average Bay Inflows v. 3-Year D.O. Violation Rates**

| Monthly Span for Inflow Average | Spearman R | p-level | Kendall Tau | p-level |
|---|---|---|---|---|
| Sep-Jun | 0.64 | <0.01 | 0.48 | <0.01 |
| Oct-Jun | 0.66 | <0.01 | 0.51 | <0.01 |
| Nov-Jun | 0.70 | <0.01 | 0.52 | <0.01 |
| Dec-Jun | 0.72 | <0.01 | 0.56 | <0.01 |
| Jan-Jun | 0.67 | <0.01 | 0.47 | <0.01 |
| Sep-May | 0.61 | <0.01 | 0.45 | <0.01 |
| Oct-May | 0.61 | <0.01 | 0.46 | <0.01 |
| Nov-May | 0.66 | <0.01 | 0.49 | <0.01 |
| Dec-May | 0.60 | <0.01 | 0.44 | <0.01 |
| Jan-May | 0.61 | <0.01 | 0.44 | <0.01 |

## RECOMMENDATIONS ON MONTHLY SPAN

Based on this analysis, we do not believe the September-November streamflow adds mechanistic information to the analysis, and thus we recommend that the monthly span for the hydrologic analysis remain representative of the winter-spring freshet, without addition of early fall inflows. Given the similar correlation coefficients for different monthly spans, and the relatively small data set for such computations, one should not choose between them on the basis of correlation coefficients alone. The January-May period remains of interest due to the fact that it captures the months that are most often important, and the use of this period has a strong precedent in the Bay hypoxia forecasting model.

The addition of December or June to the monthly span could also be considered. Given that calculated return periods could be sensitive to the monthly spans chosen, one manner to proceed would be to calculate the returned intervals associated with 2-4 of the primary spans of potential interest (Jan-May, Jan-Jun, Dec-May, Dec-Jun) and express the return periods as a range.

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